

HADRON SUBSTRUCTURE PROBED WITH HADRON BEAMS^{*†}

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Abstract

In this talk, I focus on the quark-gluon structure of hadrons probed using high-energy hadron beams. I start with a brief review on recent major achievements in measuring parton distributions of the nucleon, pion, and kaon, with hadron facilities at CERN and FNAL. Then I discuss a number of outstanding questions and interesting physics issues in the field, and point out their intellectual impact on nuclear physics as a whole. While advocating a continuing exploitation of hadron beams at CERN and FNAL, I strongly emphasize the role of a polarized RHIC, where a major nuclear physics program on the structure of hadrons can thrive.

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I. INTRODUCTION

Study of the quark-gluon structure of hadrons, the nucleon in particular, has becoming a major frontier in modern nuclear physics. Since mid-1970's, a large number of theoretical nuclear physicists have involved and played a major role in understanding the substructure of hadrons. In experimental nuclear physics community, a large amount of resources has been devoted to measuring properties of the nucleon that have simple and direct attribution to its substructure. One of the most visible activities in recent years has been measuring and interpreting the spin structure functions of the nucleon in deep-inelastic scattering [1].

It is simple to understand why the study of hadron structure is an exciting and promising field of nuclear physics. Since Hofstadter's measurement of the nucleon's size 1950's, its inner structure and dynamics have become a major focus for nuclear and particle physicists. Not only the nucleon is the basic constituent of the nucleus, and thus knowing its properties is crucial for solving the nuclear systems, but also it is the king of hadrons, and unlocking its secrets is an important milestone in exploring the hadron world. In 1960's, it was thought that the structure of the nucleon is just another incarnation of shell model, which had successfully explained the structure of atoms and nuclei. However, the MIT-SLAC deep-inelastic scattering experiments and the advent of Quantum Chromodynamics (QCD) had forced us to abandon the simplistic point of view and to face the full complexity of a relativistic quantum field theory. In the past twenty years, we have learned a lot about QCD and hadron physics, however, the problem of hadron structure is not completely solved. Before theorists can calculate as confidently as they did for QED, experimental probes into the structure of hadrons continue to play a pivotal role in our quest.

The goal of this talk is to review accomplishments made in this field using high-energy hadron beams and to point out their future prospects in solving outstanding questions. Before I plunge into details, I would like to point out some important virtues of hadron beams from a theorist point of view. First of all, hadron beams are effectively beams of quarks and gluons. There are variety of hadron beams: proton, antiproton, pion, kaon, etc., which can be used for different studies. Second, there are many hard scatterings which one can select for probing different aspects of hadron structure, e.g., jet, direct photon, Drell-Yan, heavy mesons, and weak bosons (W and Z) production. Lastly, experimenters can now produce high-energy proton beams with polarization, which allows us to study important spin-dependent parton distributions.

II. MAJOR ACCOMPLISHMENTS OF THE PAST

Direct probe of the quark-gluon content of hadrons with hadron beams started with low-energy facilities, such as J/ψ production at AGS, in the 70's. However, experiments at these facilities are barely explainable with perturbative QCD, and the statistical accuracy of the data does not allow a meaningful extraction of parton distributions. Targeted studies of quark and gluon distributions at hadron facilities began in the 80's at CERN SPS and FNAL Tevatron. With beam energies of 200 GeV and higher, there is little question that hard subprocesses are perturbative and radiative effects are calculable in perturbation theory. For fixed target experiments, important observables include Drell-Yan pairs, direct photon, and heavy-quarkonium production. In the simple parton model, they are directly related to

anti-quark and gluon distributions, which are less constrained by deep-inelastic scattering data. In the following subsections, I briefly review the main results of these studies. I apologize for not being complete.

A. Direct-photon production

Direct photon production provides a sensitive probe to the gluon distribution in hadrons. From deep-inelastic scattering (DIS) data, it was determined indirectly that gluons carry 50% of the nucleon's momentum in infinite momentum frame [2]. For certain very high energy experiments, the gluon content of a hadron plays a more dominant role than the quark content. Thus an accurate measurement of the gluon distribution is extremely important. In DIS process, the total cross section depends on gluons only at the next-to-leading order. However, direct photon production through Compton process $gq \rightarrow \gamma q$ involves the gluon distribution starting at the tree level.

Many experiments have measured direct photons in proton-induced collision [3]. Here I would like to mention particularly the WA70 experiment at CERN SPS, in which prompt photons with p_T in the range of 4.0 to 6.5 GeV and $x_F < 0.45$ were measured. The result is shown in Fig. 1 for different x_F ranges. The solid and dashed curves correspond to two versions of the gluon distribution by Duke and Owens [5], which were obtained by fitting data from deep-inelastic scattering, the Drell-Yan process, and J/ψ production. Clearly the data is discriminatory and favors the “soft” gluon distribution,

$$xG(x) = (1 + 9x)(1 - x)^6, \quad (1)$$

at $Q^2 = 4\text{GeV}^2$ with $\Lambda_{\text{QCD}} = 200$ MeV. Of course, one shall not be satisfied with testing certain parameterizations. The data shall be used for global fits [6].

J/ψ production can also constrain the gluon distribution. However, it has limitations. For instance, a model for the soft process $c\bar{c} \rightarrow J/\psi$ must be used to connect the cross section with the gluon distribution.

B. Drell-Yan process and the sea quark distributions in the nucleon

In Drell-Yan process, quarks and antiquarks from hadron beams and nuclear targets annihilate each other and produce virtual photons that subsequently decay into lepton pairs (l^+l^-). A great virtue of the process is that it depends on valence and sea distributions separately. Through a combination of experiments with selected kinematics, one can measure sea quark distributions accurately. Of course, combining parity-conserving and parity-violating structure functions from neutrino DIS, one can also extract the quark sea. However, Drell-Yan data provides not only a cross check, but also a better alternative in certain cases.

There are a number of interesting questions that one can ask about the sea quark distributions in the nucleon: Are the sea distributions measured in Drell-Yan scattering consistent with that determined from neutrino DIS? Is the up-quark sea in the nucleon the same as the down-quark sea in the nucleon? Are the sea-quark distributions modified in a nuclear environment? These questions have been partially answered with a number of excellent experiments.

Three experiments have made comprehensive measurements of large mass $\mu^+\mu^-$ pairs in proton-induced collisions: E288 [7] and E605 [8] experiments at FNAL, and NA3 [9] experiment at CERN. An example of the data is shown in Fig. 2. With the order- α_s perturbative QCD corrections, the data is consistent with the anti-quark distribution extracted from neutrino scattering. Together, they provide accurate constraints on the sea quark distributions. One interesting point here is that both E288 and E605 data show a positive slope for the cross section at $y = 0$ for (see Fig. 3). Since the Cu target contains more neutrons than protons, it is natural to conclude that \bar{u} is suppressed relative to \bar{d} in the proton.

Actually, the assertion that the up-quark sea is not the same as the down-quark sea is also a natural explanation for the violation of the Gottfried sum rule [10],

$$\int_0^1 \frac{(F_2^p(x) - F_2^n(x))}{x} dx = \frac{1}{3} + \frac{2}{3} \int_0^1 dx [\bar{u}(x) - \bar{d}(x)] = 0.240 \pm 0.016 , \quad (2)$$

which is measured by EMC at $Q^2 = 4 \text{ GeV}^2$. To get a decisive evidence that up and down seas are not symmetric, Garvey *et al.* proposed to compare the Drell-Yan cross section in $p + p$ and $p + d$ collisions [11]. A recent experiment at CERN [12] has measured one data point at $x = 0.18$, where $\bar{u}/\bar{d} = 0.51 \pm 0.04 \pm 0.05$. This is a first direct evidence that the quark sea is not isospin singlet.

Motivated by the EMC effect that quark distributions in a nucleus are different from these in a nucleon [13], the E772 experiment [14] at FNAL measured for the first time the nuclear dependence of sea quark distributions through Drell-Yan μ -pair production. In the x range $0.1 \sim 0.3$, they found that the sea quark distributions in measured nuclei are the same as that in a nucleon (see Fig. 4). Below $x = 0.1$, the sea-quark shadowing is discovered. The effects, however, are less pronounced than the combined valence and sea shadowing measured by EMC (modulo Q^2 evolution). The result implies that the momentum fraction carried by sea quarks in a nucleus is reduced through shadowing. The result also rules out certain models that are motivated to explain the EMC effects. This high-precision, definitive experiment is very impressive.

C. Parton distributions in the pion and kaon

The parton distributions in the pion cannot be measured in deep-inelastic scattering. The only probe is through high-energy $\pi - N$ scattering, detecting Drell-Yan pairs and direct photon production. The valence distribution in the pion was first investigated by E444 collaboration at Fermi Lab. High statistics and larger kinematic coverage experiments were later done by NA3 and NA10 collaborations at CERN, E615 collaboration at FNAL.

The valence quark distribution is well-determined from the data measured in NA10 [15] and E615 [16] experiments. The $x \rightarrow 0$ and $x \rightarrow 1$ behavior of the distribution is consistent with expectations of Reggie theory and the quark counting rule. The gluon distribution can be extracted from the direct photon production data from the WA70 experiment [17]. The sea quark distribution is less well-determined, primarily because the data only exists in the $x_\pi > 0.2$ region. A recent fit to these experiments by Sutton, Martin, Roberts, and Stirling are shown in Fig. 5 [18]. One interesting consequence of the data is that the color fields in

the pion approach that in the QCD vacuum in the chiral limit, a feature that is consistent with the postulate that the pion is a collective excitation of the QCD vacuum [19].

Higher-twist effects were observed in the angular distribution of the Drell-Yan pairs. At the leading twist level, the angular distribution goes like $1 + \cos^2 \theta$. However, as $x_\pi \rightarrow 1$, that is, when the valence quark carries all the momentum of the impinging pion, the experimentally-observed distribution goes like $1 - \cos^2 \theta$ [20] (see Fig. 6). This is a clear indication that the twist-four effect (multi-parton coherent scattering) plays a dominant role [21].

The parton distribution in the kaon was measured by NA3 collaboration. The data indicates that the up quark distribution in the kaon vanishes quicker than that in the pion. More data is needed to get a more complete picture of parton distributions there.

III. OUTSTANDING QUESTIONS

As I said in the beginning, our theoretical knowledge about hadron structure is very limited. No one knows how to calculate parton distributions from the first principle. Various hadron models have been invented, which have their own limitations. One of the limitations is that models use effective degrees of freedom, not those of QCD. Thus it is very difficult to do a meaningful computation of, e.g., gluon distribution in a model. Ultimately, our goal is not to test models — we want to test QCD.

Before one can come up with a realistic picture of the nucleon, it is important to collect as much data as possible. The advent of BCS theory for superconductor would not be possible if without some crucial experimental data. In the case of hadron structure, one important piece of information is the spin and flavor composition of parton distributions. From QCD, one can make systematic classifications of parton observables in a hadron [22]. In the following subsections, I discuss some outstanding questions from the point of view of this classification.

A. Unpolarized Distributions

With three quark flavors, there are seven unpolarized, leading-twist distributions in a hadron,

$$u(x), \bar{u}(x), d(x), \bar{d}(x), s(x), \bar{s}(x), G(x) . \quad (3)$$

Some of these have been well measured in DIS and hadron-beam induced reactions. Some distributions, however, are less known. Some open questions are suitable for study with hadron beams.

1. *u and d sea distributions in the nucleon*

We know fairly well the average of up and down sea distributions. However, the separate distributions are not known. Sea distributions are an important window to the hadron structure. Many people believe that most of the sea quarks arise from the Q^2 evolution in

which quark pairs are created through splitting of gluons. On the other hand, sea quarks at low energy scales (intrinsic sea) are certainly related to low-energy and long-distance dynamics. The difference between up and down sea distributions will put many ideas, including Pauli-blocking effects and pion cloud, into test.

2. Strange-antistrange distributions in the nucleon

The most recent measurement of the strange quark distributions was done by the CCFR collaboration [23]. Within the precision of the data, it seems that $s(x)$ and $\bar{s}(x)$ distributions are the same. However, there are reasons to believe $s(x) - \bar{s}(x)$ is nonzero. If so, the size of this difference is very interesting and shall be measured. According to the picture of meson cloud, the valence anti-strange quark in virtual kaons present in the nucleon wave-function contributes to \bar{s} distribution, and the valence strange quark in virtual hyperons contributes to s distribution. With this mechanism, there is no symmetry between strange-anti-strange distributions. Since the total flavor charge is conserved,

$$\int_0^1 (s(x) - \bar{s}(x)) dx = 0 , \quad (4)$$

the size of $s(x) - \bar{s}(x)$ tells us the locality of quark-antiquark pairs in momentum space, a important observable of the sea.

3. Parton distributions in the kaon

One can learn a lot by comparing the parton distributions in the pion and kaon. Both particles are Goldstone bosons, however, the kaon is much heavier than the pion. The effect of the strange quark mass in the kaon structure is valuable in studying structure of Goldstone bosons.

B. Polarized Distributions

With recent measurements of the longitudinally-polarized quark distributions at CERN and SLAC [1], high-energy spin physics has becoming a hot subject. Theoretical studies revealed that there are a number of interesting spin-dependent quark-gluons distributions which have never been measured before and which have extremely important implications about the spin content of the nucleon [24]. Most of these distributions, however, cannot be measured cleanly in lepton-nucleon deep-inelastic scattering either due to chirality selection rule or due to small contribution in lepton-induced processes. On the other hand, a polarized hadron beam is far more superior for studying these observables. Let me highlight some important physics one can hope to study with a polarized proton beam.

1. Polarized gluon distribution $\Delta G(x)$

In a polarized nucleon, gluons are also polarized. The polarization contributes to the nucleon spin=1/2. Normally, one would expect the contribution to be some fraction of the

total. However, some advocate, according to a study of the axial anomaly [25], that the gluon polarization contributes several units of angular momentum. If so, there must be mechanisms to cancel this large gluon-spin contribution. However, before one starts to look for the cancelation, one must measure $\Delta G(x)$ in the full x range and study its sum rule. So far, however, nothing is known about $\Delta G(x)$ experimentally.

2. Polarized quark sea

Another interpretation of the “spin crisis” is that the sea quarks have large polarization. This is deduced from the hyperon β -decay data plus use of the flavor SU(3) symmetry. One can verify this deduction through measuring the polarized distributions for up, down, and strange seas independently. Such data, if available, will test SU(3) symmetry, very important from the point of hadron structure.

3. Transversity distribution $h_1(x)$

For a spin-1/2 nucleon, there are a total of three distributions which characterize the quark state in leading order high-energy scattering: the unpolarized quark distribution and quark helicity distribution we have talked about above, and the quark transversity distribution. The last distribution shows up in a transversely polarized nucleon and counts the net number of quarks polarized along the transverse polarization of the nucleon. In non-relativistic quark model or in models with no parton interactions, the transversity distribution is the same as the helicity distribution. Jaffe and I have derived a sum rule for the quark distributions [24],

$$\int_0^1 h_1^q(x, Q^2) dx = \delta q \quad (5)$$

where δq is the tensor charge of the nucleon. A recent estimate indicates that $\delta u = 1.0 \pm 0.5$ and $\delta d = 0.0 \pm 0.5$ [26]. A measurement of the tensor charge is important to understand the relativistic effects and the spin structure of the nucleon.

4. Twist-three parton distributions

There are a number of twist-three distributions which are interesting. The most famous one is $g_2(x)$, present in a longitudinally polarized nucleon and measurable in deep-inelastic scattering [27]. Another distribution similar to $g_2(x)$ is $h_2(x)$, present in a transversely polarized nucleon [24]. There are also general twist-three distributions which depend on two Feynman variables [28]. Higher-twist distributions appear in coherent parton scattering, which is not present in Feynman’s parton model. All twist-three distributions can be accessed in hadron-beam induced processes.

IV. FUTURE EXPERIMENTAL PROSPECTS

To probe directly the quark-gluon constituents of the nucleon, one must ensure the probes are clean. That means one must resort to hard processes in which quark and gluon scattering is perturbative and can be calculated in perturbative QCD. As a consequence, we need hadron beams at several hundred GeV. At present time, such facilities are limited to SPS at CERN, Tevatron at FNAL, and possibly HERA at DESY. In the near future, RHIC will be added to the list. In the last few years, we have witnessed increasing involvement at these facilities by nuclear experimentalists. Such involvement shall continue with clear physics goals and high-quality experiments. In the following, I will discuss some prospects for the two US facilities.

A. Tevatron at FNAL

As I have discussed, the hadron beams at FNAL have already played important roles in probing parton distributions. I think the nuclear community shall continue to use these beams to make further explorations of some of the outstanding questions. Some studies can only be made with hadron beams, for instance, the quark and gluon distributions in pions and kaons. Kaon beams have the unique capability to probe the strange sea in the nucleon. Unfortunately, because they are secondary beams, the intensity may not be suitable for high-precision measurements.

One excellent example for future experiments at FNAL is E866 experiment proposed by G. Garvey *et. al.*, which was approved in December 1992 and will start to take data in the beginning of the next year. According to the proposal [29], the experiment makes a precise measurement of Drell-Yan yields from hydrogen and deuterium. The ratio of these yields is used to infer the ratio $\bar{u}(x)/\bar{d}(x)$ in the proton, over the x interval between 0.03 to 0.3. According to the parton model, one has,

$$2 \frac{\sigma_{\text{DY}}(p + p)}{\sigma_{\text{DY}}(p + d)} = 1 - \frac{\bar{d}(x) - \bar{u}(x)}{\bar{d}(x) + \bar{u}(x)}. \quad (6)$$

The expected statistical accuracy together with several model predictions for the ratio is shown in Fig. 7 [30]. Clearly, the experiment will make a first precise measurement of the asymmetric sea and the data provides a definitive test of various models.

B. RHIC

Although RHIC is not build for learning hadron structures, it turns out that it offers excellent opportunities for such studies. The most exciting possibility is of course a polarized RHIC. Thanks to an ingenious invention called Siberian snake [31], one can now have a polarized hadron beam at few hundred GeV. With 250 GeV longitudinally or transversely-polarized proton beams colliding at luminosities up to $2 \times 10^{32} \text{ cm}^{-2}\text{sec}^{-1}$, one can make state-of-art studies of polarized distributions in the proton.

Even without polarization, one can already do some interesting physics with RHIC hadron beams. For instance, two recent studies [32,33] show that by comparing W and

Z production from $p + p$ and $p + d$ collisions, one can extract the up and down quark distributions separately. These measurements can provide a cross-check on results from E866 measurements and extend them to smaller x region.

The RHIC spin collaboration was formed three years ago to study the feasibility of a polarized RHIC and to make proposals for physics program at such machine [34]. According to the proposal, the major components for the acceleration of polarized beams to RHIC top energy are shown in Fig. 8. Polarized protons are produced at the present AGS source and are accelerated to 200 MeV with the LINAC. They are captured in the AGS Booster and are further accelerated to 1.5 GeV and then transferred to AGS where they are accelerated to 25 GeV. A partial Siberian snake is needed to maintain the polarization at AGS. When protons are transferred to RHIC for acceleration to 250 GeV, two Snakes are needed for correcting the depolarization effects. In a steady running, one expects 70% beam polarization.

The two RHIC detectors, PHENIX and STAR, will be used to measure Drell-Yan pairs, direct photons, jets, W and Z , and heavy meson production. With these probes, one can make systematic measurements of polarized quark and gluon distributions in the nucleon.

1). *Gluon helicity distribution* can be measured in jet and direct photon production. For low transverse momentum jets, e.g. $10 < p_T < 20$ GeV/c, single and di-jet productions are dominated by gluon-gluon fusion. The double spin asymmetry for longitudinally-polarized collision is

$$A_{LL} = \frac{\Delta G(x_1)}{G(x_1)} \frac{\Delta G(x_2)}{G(x_2)} a_{LL}(gg \rightarrow gg) , \quad (7)$$

where a_{LL} is the asymmetry at the parton level. The range of x covered at RHIC extends at least from 0.05 to 0.3. Direct photons are produced through $q\bar{q}$ annihilation and $q - g$ Compton process. The latter is dominant in polarized scattering and produces the following asymmetry,

$$A_{LL} = \frac{\Delta G(x_1)}{G(x_1)} \frac{\Delta q(x_1)}{q(x_1)} a_{LL}(qg \rightarrow q\gamma) , \quad (8)$$

where the valence quark distributions can be taken from DIS data.

2). *Polarized sea quark distributions* can be measured through Drell-Yan and weak bosons (W and Z) production [35]. In Drell-Yan process, the double spin asymmetry is,

$$A_{LL} = a_{LL}(q\bar{q} \rightarrow l^+l^-) \frac{\sum_f e_f^2 [\Delta \bar{q}(x_1) \Delta q(x_2) + \Delta \bar{q}(x_2) \Delta q(x_1)]}{\sum_f e_f^2 [\bar{q}(x_1) q(x_2) + \bar{q}(x_2) q(x_1)]} \quad (9)$$

Without the sea quark polarization, the asymmetry vanishes. For weak boson production, one can define both single-spin and double-spin asymmetry. The single-spin asymmetry violates the parity. Both symmetries are sensitive to sea-quark polarizations.

3). *The quark transversity distribution* can be measured similarly in Drell-Yan and Z -boson production [32,36]. Since the interference between left and right-hand annihilations is required, W production gives a vanishing asymmetry.

4). *Twist-three quark-gluon and gluon-gluon correlations* can be measured through single-spin asymmetry associated with pion production, single-jet production etc.

To sum up, hadron beams have helped us to learn a great deal about the quark and gluon distributions of hadrons. They will continue to play an important role in our future research in the field. A polarized RHIC collider offers a unique and interesting physics opportunity to the nuclear community.

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FIGURES

FIG. 1. Invariant cross section for $pp \rightarrow \gamma X$. a) $-0.35 < x_F < -0.15$. b). $-0.15 < x_F < 0.15$. c). $0.15 < x_F < 0.45$. d). $-0.35 < x_F < 0.45$ from WA70 experiment. The dashed and solid curves represent the prediction from Duke and Owens hard and soft gluon distributions.

FIG. 2. Drell-Yan cross section measured by NA3 and E605 collaborations.

FIG. 3. Drell-Yan cross section measured by NA3 and E605 collaborations, plotted as a function of the rapidity of virtual photons.

FIG. 4. Ratios of the Drell-Yan dimuon yield per nucleon for positive x_F from E772 collaboration.

FIG. 5. Valence, sea, and gluon distributions obtained by Sutton *et al.* through fitting NA10, E615, and W70 experiments.

FIG. 6. The parameter λ , as defined in the angular distribution of the Drell-Yan pairs, $1 + \lambda \cos^2 \theta$, extracted from E605 experiment.

FIG. 7. Predictions of Drell-Yan cross section ratios for various models. The expected sensitivities for E866 and the recent N51 results are also shown (from Ref. [30]).

FIG. 8. Polarized proton collision at Brookhaven.

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